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COUPLING ISSUES ASSOCIATED WITH ELECTROMAGNETIC VULNERABILITY (EMV) TESTING OF VEHICLES OVER GROUND

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Abstract—Electromagnetic Vulnerability (EMV) testing of ground vehicles and helicopters is (by necessity) performed in the immediate presence of ground surfaces (natural earth, asphalt, concrete, ship decks, and other finitely conducting grounds). The impact of the nature of these grounds on the EM coupling to the various vehicles being tested is the focus of this work. As one approach to addressing these issues quantitatively, personnel at Redstone Test Center Electromagnetic Environmental Effects (RTC/E3) Division have combined measurements on a semi-canonical physical structure along with EM modeling. In particular, a hollow 25 foot long, 4 foot diameter aluminum cylinder with a finite slot ($\sim$ 8 in wide) running along its entire length is positioned over (and near to) a finite conducting ground plane. Measurements of the electric fields produced both in the slot aperture and inside the hollow cylinder by an external log period dipole antenna (LPDA) positioned (broadside to the horizontal cylinder) approximately 5 m away radiating both vertical and horizontal polarizations, respectively, are presented and discussed. The entire experimental setup (aluminum cylinder, finite aluminum ground plane, and radiating LPDA) are enclosed inside an RF anechoic chamber (inside dimensions between the respective tips of the anechoic pyramids of approximately $19\,\mathrm{m} \times 9.0\,\mathrm{m} \times 5.0\,\mathrm{m}$). A moment method

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14. ABSTRACT

Abstract|Electromagnetic Vulnerability (EMV) testing of ground vehicles and helicopters is (by necessity) performed in the immediate presence of ground surfaces (natural earth, asphalt, concrete, ship decks, and other ?nitely conducting grounds). The impact of the nature of these grounds on the EM coupling to the various vehicles being tested is the focus of this work. As one approach to addressing these issues quantitatively, personnel at Redstone Test Center Electromagnetic Environmental E?ects (RTC/E3) Division have combined measurements on a semi-canonical physical structure along with EM modeling. In particular, a hollow 25 foot long 4 foot diameter aluminum cylinder with a ?nite slot (? 8 in wide) running along its entire length is positioned over (and near to) a ?nite conducting ground plane. Measurements of the electric ?elds produced both in the slot aperture and inside the hollow cylinder by an external log period dipole antenna (LPDA) positioned (broadside to the horizontal cylinder) approximately 5m away radiating both vertical and horizontal polarizations, respectively, are presented and discussed. The entire experimental setup (aluminum cylinder, ?nite aluminum ground plane, and radiating LPDA) are enclosed inside an RF anechoic chamber (inside dimensions between the respective tips of the anechoic pyramids of approximately 19m ? 9:0m ? 5:0 m). A moment method model (CARLOS) is also developed and the ?elds in the aperture and inside the cylinder are compared to the measured ?elds.

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model (CARLOS) is also developed and the fields in the aperture and inside the cylinder are compared to the measured fields.

1. INTRODUCTION

As per requirements outlined in Military Standards [1] and Aeronautical Design Standards [2], designated DoD testing laboratories deem it necessary to expose functional complex military systems (helicopters, rocket launchers, personnel carriers, humvees (HMMWVs), unmanned ground and air vehicles, etc.) to EM environments that represent potential threats such systems might encounter in friendly forces in the CONUS as well as hostile forces on foreign soils. In carrying out such EM testing, issues often arise as to the effect of the presence (or absence) of a ground near the vehicle. Of course, ground vehicles are deployed and operate inherently close to (on) the ground. However, this "ground" may physically be described as natural earth, paved surfaces such as concrete or asphalt, or even large metal surfaces such as the deck of ships. Also, it is apparent that helicopters and unmanned air vehicles operate primarily at heights significantly above the ground. Even these "in flight" vehicles begin their missions sitting or taxiing on natural earth, asphalt or concrete, or the metal decks of ships. Therefore, it is useful to ascertain how the presence of these various different ground surfaces impacts the coupling of EM fields to these complex vehicles and/or weapon systems.

The investigation discussed here addresses the effects of a finite-sized aluminum ground plane on coupling to the inside of a metallic enclosure (open-ended right circular cylinder) through a slotted aperture. In particular, RTC/E3 personnel have constructed a hollow aluminum cylinder 7.62 m long (25 feet) and of circular cross section 1.22 m (4 feet) in diameter. The cylinder has a slot cut all along its length of width $\sim$ 8 in, and this slot is positioned on the cylinder centered along a line horizontally even with the cylinder axis. This aluminum cylinder is open-ended, and it is positioned at varying heights above the ground. The ground is a finite conducting (aluminum) plane (8.4 m wide by 12.6 m long) with the aluminum cylinder positioned with the geometric axis of the cylinder located 2.1 m from the end of the ground plane. The 25 foot cylinder, a radiating LPDA separated from the cylinder by 5 m, and the 8.4 m $\times$ 12.6 m finite ground plane are all located inside an anechoic chamber with inside dimensions of 5.0 m $\times$ 9.0 m $\times$ 19 m.

Consider the geometry shown in Figures 1, 2, and 3. Measured and modeled coupling data are discussed for heights of 0.940 m, 1.295 m, and 2.515 m from the cylinder axis to the ground plane. The LPDA is

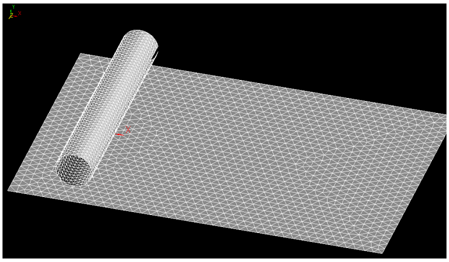

Figure 1. Model illustration of slotted cylinder relative to ground plane.

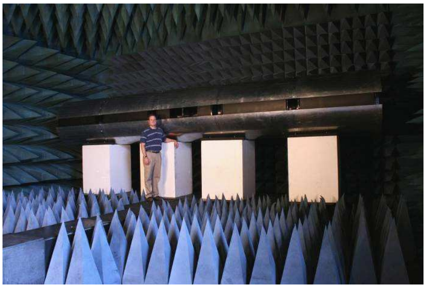

Figure 2. Slotted cylinder in anechoic chamber (floor covered, no ground plane).

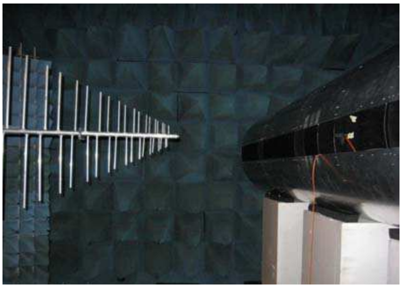

Figure 3. Slotted cylinder in anechoic chamber relative to LPDA.

located on the "opposite end" of the long dimension of the ground plane from the cylinder with the forward apex of the LPDA located 5 m from the aperture of the cylinder with the elements of the "rear" reflector dipole located approximately 2 m from the end of the aluminum ground plane. (The LPDA oriented for vertical polarization is shown in Figure 3 with the antenna moved forward such that the LPDA apex is located approximately 1 m from the slot aperture for photographic purposes.)

EM coupling measurements and modeling of this geometry (aluminum cylinder with slot being illuminated by the LPDA) without the presence of the aluminum ground plane has been addressed previously [3–8]. In these previous references, it has been demonstrated with both physical measurements and analytical/numerical modeling that coupling through the slot aperture to the interior of the hollow cylinder is dominated by the natural circular cylindrical cavity resonance field distributions that are excited through the slot aperture.

These specific transverse electric (TE) and transverse magnetic (TM) resonance frequencies/modes are outlined in detail in the previously referenced studies so the specific spatial distributions will not be repeated here. Of course, this study adds the presence of a conducting ground plane to this previously investigated slotted right circular cylinder [6]. Again, it will be demonstrated and observed that the internal (and aperture) fields continue to be dominated by the internal resonance field distributions even in the presence of the ground plane.

2. MEASURED AND MODELED APERTURE AND INTERIOR FIELDS

The first issue to be explored in the data here is the effect of the height of the cylinder axis on the fields (total electric) in the aperture and at positions inside the cylinder.

For these data (Figures 4, 5, 6, and 7), the LPDA was radiating at a height (the boom supporting the numerous elements) that was equal to the height of the cylinder axis above the ground plane. The slot aperture (representing an arc of 20 deg of the total circumference of the cylinder) is positioned such that the radiating antenna is pointed

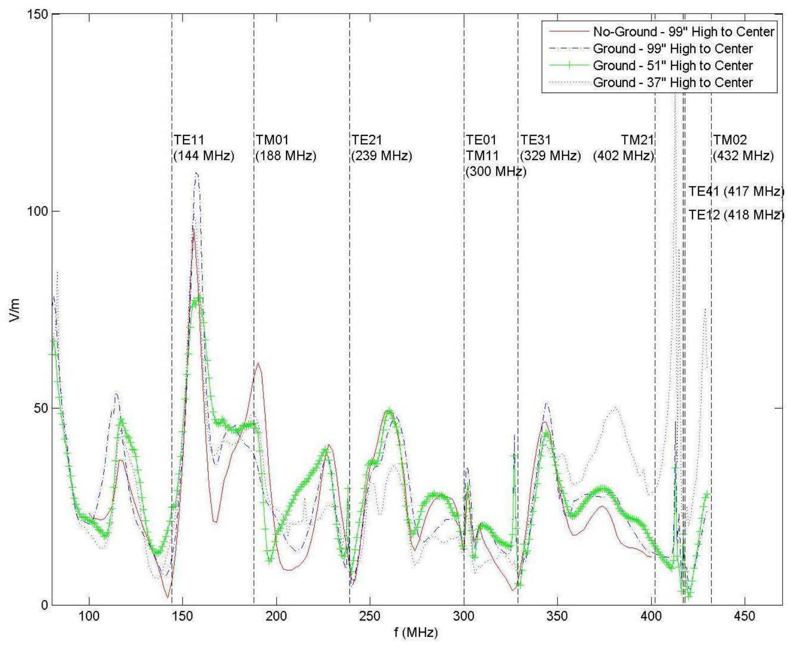

Figure 4. Aperture fields, vertical/TE, 5 m separation.

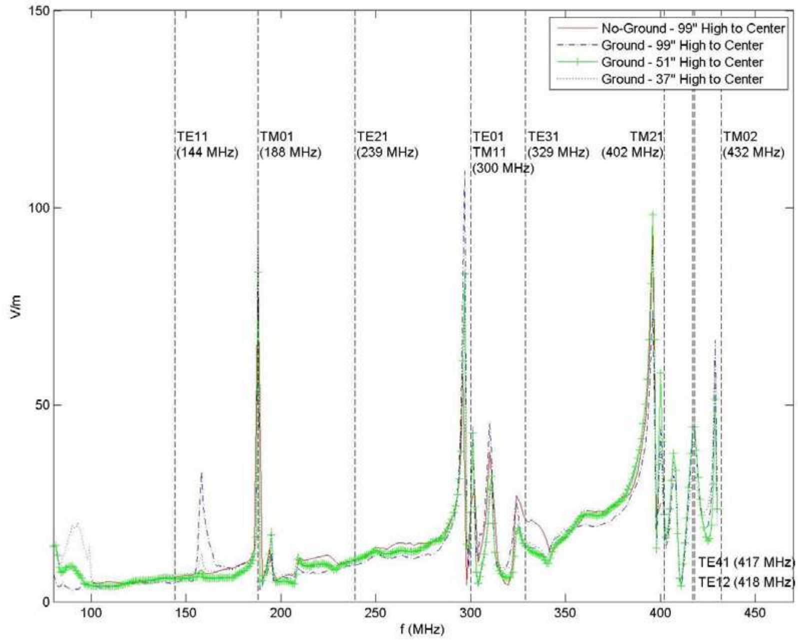

Figure 5. Aperture fields, horizontal/TM, 5 m separation.

at ("shining directly into") the slot aperture. Both polarizations are considered with the vertically polarized orientation being referred to as the TE (radiated electric field perpendicular or transverse to the cylinder axis) and the horizontally polarized orientation being referred to as the TM (radiated magnetic field perpendicular or transverse to the cylinder axis). These TE and TM polarizations may also be considered appropriately designated w/r/t the TE and TM (to the cylinder axis) of the hollow, infinitely long right circular cylinder.

Consider the plots of the measured (total) electric field (vector sum of the three orthogonal components) in the slot aperture as shown in Figures 4 and 5 for the TE and TM cases, respectively, for the three specific heights of the cylinder axis above the ground of 0.940 m (37 in), 1.295 m (51 in), and 2.515 m (99 in), respectively, as well as the results obtained for the case with the ground absent (actually the floor of the anechoic chamber was covered with appropriate absorbing anechoic material). The aluminum cylinder dimensions were chosen to represent a very crude (yet mathematically and numerically amenable geometry) 1/2 scale model of the fuselage of a Blackhawk (UH-60) helicopter. The lowest height above the ground plane represents the approximate height such a 1/2 scale model would sit (on its landing

gear or skids) above the actual ground surface such as the metallic deck of a ship or over a concrete or asphalt runway or taxiway.

The hollow cylindrical waveguide TE and TM modes (and associated circularly cylindrical waveguide cutoff frequencies) are also indicated on these plots as vertical dashed lines. The electric field amplitudes in the aperture are those fields produced in the slotted aperture by a nominal "free" electric field of 20 V/m existing at the position of the slotted aperture produced by the LPDA when the cylinder is absent (while the aluminum ground plane is present). This "free" electric field is similar in nature (but not amplitude) to the ambient "free" fields required in military and aeronautical standard EMV testing requirements.

As discussed in some detail in several of the references, the presence of the slot aperture "impedance loads" the interior of the cylinder such that the frequencies of the TE modes are increased and the frequencies of the TM modes are decreased slightly. Furthermore, the presence of both TE and TM modes for both excitations suggests that the "finiteness" of length of the cylinder contributes to some excitation of the TM modes for the vertical polarization and the TE modes for the horizontal polarization, respectively. Also, there is

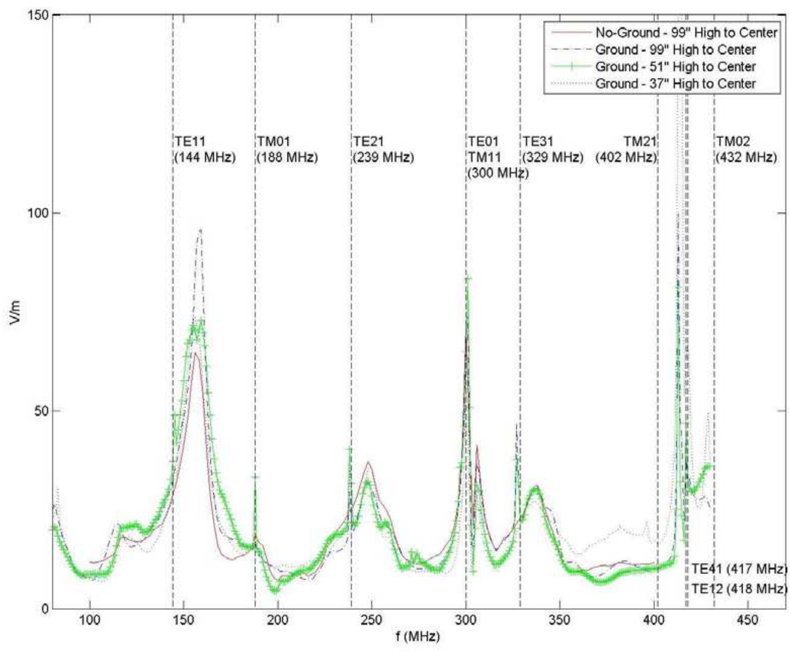

Figure 6. Internal fields, vertical/TE, 5 m separation.

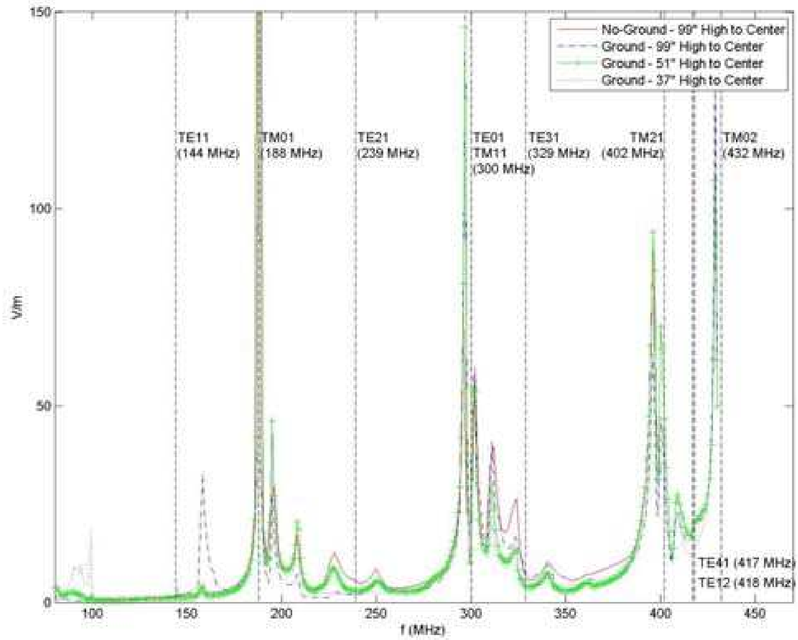

Figure 7. Internal fields, horizontal/TM, 5 m separation.

some evidence of additional responses at other frequencies that may represent some form of "hybrid modes" that are neither purely TE nor TM. (See discussion in [6] for further details.)

Figures 6 and 7 present the "spatial average" of the electric fields (actually the square root of the averaged power densities) measured inside the hollow cylinder (at the 13 interior points as indicated in Figure 8) when the applied "free" field radiated by the LPDA is 20 V/m. This free field is measured at the position of the slotted aperture when the ground plane is present but the slotted cylinder is not present. This same level of power is fed to the LPDA with the cylinder present to produce the interior fields shown in Figures 6 and 7.

Of course, the main observation pertaining to these four plots is the effect of the ground plane and its height on the coupling of the TE and TM excitations displayed in the aperture fields and interior fields. For both vertical electric field excitation (TE case) and horizontal electric field excitation (TM case), it is apparent that the presence of the ground does not result in order of magnitude changes to the overall responses of the slotted cylinder except at a very few specific narrowband frequencies associated with some resonance of the cylinder cavity.

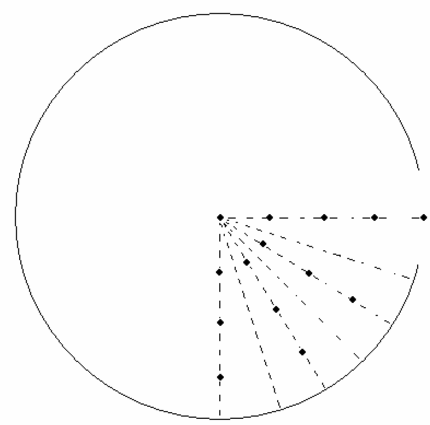

Figure 8. Cylinder cross section with internal and aperture probe positions.

Specifically, for the aperture electric field for the TE excitation, near the "hybrid mode" around 118 MHz, the maximum variation between the "no ground" case and the three specific height variations is approximately +3.3 dB, respectively. Near the TM01 mode, this variation is approximately −2.6 dB. Again, around another "hybrid mode" near 375 MHz, this variation is approximately +6.0 dB. Higher differences may be present above 400 MHz, but unfortunately there were no measurements of these fields for the "no ground" case.

Similarly, for the aperture electric field for the TM excitation, the maximum variation between the "no ground" case and the height variations is approximately +3.4 dB near the TE_{11} response around 160 MHz, and it is approximately +5.5 dB near the "hybrid mode" around 380 MHz. These variations for the internally averaged fields are similar for the TE excitations, but exhibit variations as high as 15–20 dB for the TM variations. (See graphical comparisons in Figure 7 around 100 MHz and 160 MHz.)

Virtually all the "modes" excited in the case where there is no ground present are also excited to one degree or another when the ground plane is present regardless of the height of the cylinder above the ground plane. Specifically, in the TM case, it is evident that the presence of the ground plane has less effect on the coupling to the aperture fields. (This may be expected since the "effective cutoff frequency" for the TM mode excitation is around 700 MHz whereas there is no "effective cutoff frequency" for the TE mode excitation.)

Measurements of these interior fields (and the implied effective

power densities) have direct relevance to EMV testing of helicopters and other vehicles and hardware when there is a man-in-the-loop. When personnel are present, the applied field environment is limited to field levels (and concomitant time exposures) prescribed in various DoD and industrial guidelines [9, 10]. The fields presented in these two figures (Figures 6 and 7) indicate clearly that at certain frequencies associated with specific interior resonances, these interior fields (actually spatially averaged composites) may exceed the applied "free" field by an order of magnitude or more. Such instances present serious limitations on EMV testing when personnel are inside the vehicles being radiated by the high level EM fields required in the appropriate military and aeronautical design standards.

The previous plots of fields represent values measured with a calibrated electric field probe positioned in the aperture and at specific points inside the cylinder when the LPDA is radiating the prescribed "free" electric field of 20 V/m for each polarization (vertical — TE case and horizontal — TM case) in the presence of a finite aluminum ground plane. Because of the limitations of performing these measurements inside an anechoic chamber, questions arise concerning the effects of the finite size of the aluminum ground plane placed under the cylinder — LPDA geometry. In the following paragraph, the size and positioning of a finite ground is addressed by comparing the fields produced (with the CARLOS moment method model) by a plane wave coupling to a slotted conducting cylinder over two different sized (and shaped) finite ground planes.

Using CARLOS, a numerical model of this geometry of a 25 foot long, 4 foot diameter hollow conducting cylinder with axial slot width of approximately 8 in running parallel to its axis has been developed. The cylinder axis is centered 0.940 m above a finite ground plane of dimensions 10 m × 10 m. A uniform plane wave with electric field of 20 V/m is propagating horizontally (parallel to the ground plane) shining directly into the slotted aperture. Calculations of the fields produced in the slotted aperture and at several positions inside the hollow cylinder were carried out. These calculations were compared to similar calculations for the geometry representing the more realistic situation existing in the RTC/E3 slotted cylinder/LPDA/ ground plane geometry located inside an anechoic chamber. For the more realistic case, the CARLOS model is exercised for a slotted cylinder positioned with the cylinder axis again 0.940 m above the aluminum ground plane but situated 2.1 m from one end of the ground plane (see Figure 1). The aluminum ground plane is 8.4 m by 12.6 m with a plane wave of 20 V/m propagating from the end opposite the cylinder and shining directly into the slotted aperture. Careful perusal of

these comparisons revealed that the electric fields produced in the apertures and at interior points inside the hollow cylinder for both cases (the 10 m × 10 m ground plane vs the 8.4 m × 12.6 m ground plane) are virtually indistinguishable. From these numerical comparisons, it was concluded that the finite aluminum ground plane for the physical measurements was sufficiently large enough to assume that it was essentially of infinite horizontal extent, and that it sufficiently "captured" the general effect of a conducting ground under the cylinder.

Comparisons are shown in Figures 9 and 10 of the aperture fields for the TE and TM cases between the measured and modeled data. These data compare aperture fields for the specific geometry where the axis of the cylinder is 0.940 (37 in) above the finite aluminum ground plane. The finite ground plane is the same as that used in the second CARLOS model addressed above. This ground plane is 8.4 m by 12.6 m with the cylinder axis 2.1 m away from one end of the ground plane with the plane wave propagating from the other end. For the measured values of aperture fields, the LPDA is positioned (again) with its forward apex 5 m from the slotted aperture. Superimposed on these curves of the field produced in the aperture with the slotted

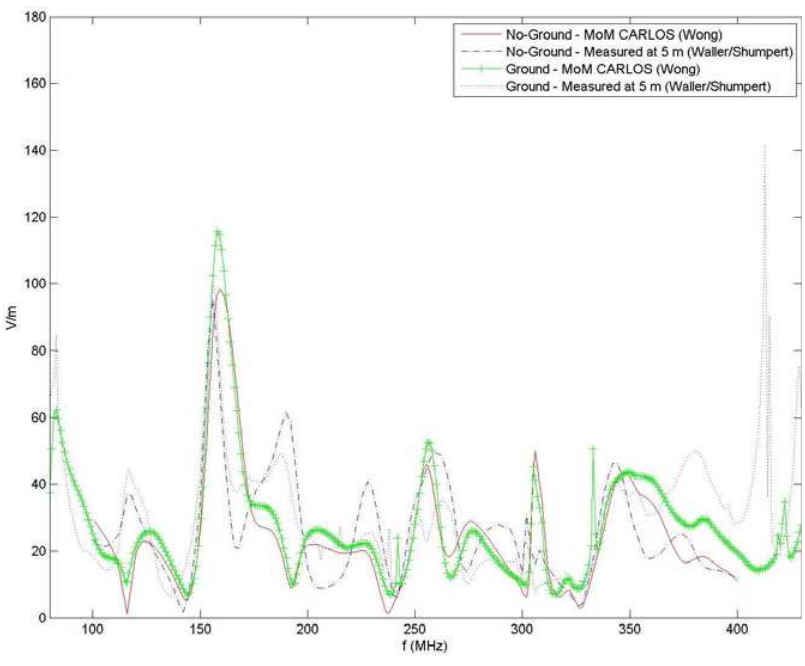

Figure 9. Aperture fields, vertical/TE, measured vs. modeled.

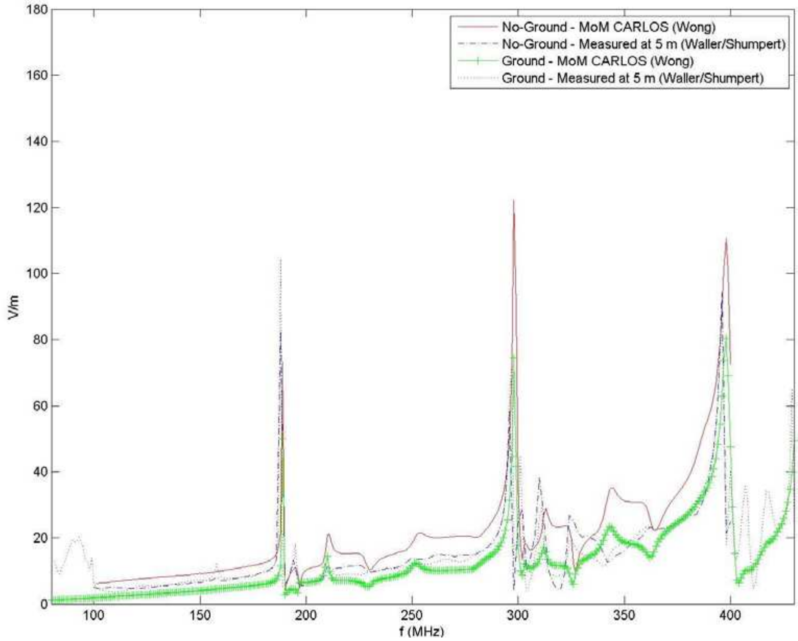

Figure 10. Aperture fields, horizontal/TM, measured vs. modeled.

cylinder in the presence of the finite ground plane are the similar data plotted for the cases where the ground planes are absent (or in the measured case, the ground is covered and treated with anechoic material to significantly reduce the ground reflection).

It is encouraging (and somewhat satisfying) to observe the relatively close agreement between the CARLOS model aperture fields (excited by the uniform plane wave) and the measured aperture fields (excited by the LPDA antenna approximately 5 m away). In the comparison of the "no ground" cases for the TE polarization, it is evident that the "physical" case measured fields exhibit some significant differences from the CARLOS model, specifically at certain frequencies where we have previously suggested that "hybrid modes" may be excited. These "hybrid modes" may be excited more in the "physical" case due to the limited distance from the LPDA, due to the cross polarized nature of the LPDA fields, and also due to the non-insignificant dimensions of the electric field probes used to obtain the measured data.

Again it is seen that although there are certainly some differences due to the presence of the ground plane, the overall coupling to the aperture fields is dominated by the internal resonances of the cylinder.

One additional observation concerning modeling of these effects may be informative. In the forerunner paper to this current work [6], the modeling of coupling to a slotted cylinder includes not only the three-dimensional (3-D) CARLOS results for the plane wave excitation of the slotted finite length cylinder, but it also includes data derived from a two-dimensional (2-D) model of an infinite slotted cylinder based on a series solution of appropriate Fredholm integral equations. For the situation where the conducting ground plane is not present, comparisons of the results of the plane-wave excited 2-D model are quite favorable to the plane-wave excited 3-D CARLOS model and to the measured aperture and interior fields excited by an LPDA approximately 5 m away.

Unfortunately, attempts to extend this 2-D model to include the presence of an infinite ground plane have proven (so far) to be problematic. The results of the 2-D model exhibit much of the expected spectral behavior as demonstrated in the 3-D CARLOS model as well as the measured aperture data. In particular, comparisons of the 2-D model for the TM cases reveal high correlations of both the spectral nature (dominated by the cylinder internal resonances) and the coupled amplitude of the electric fields produced in the aperture.

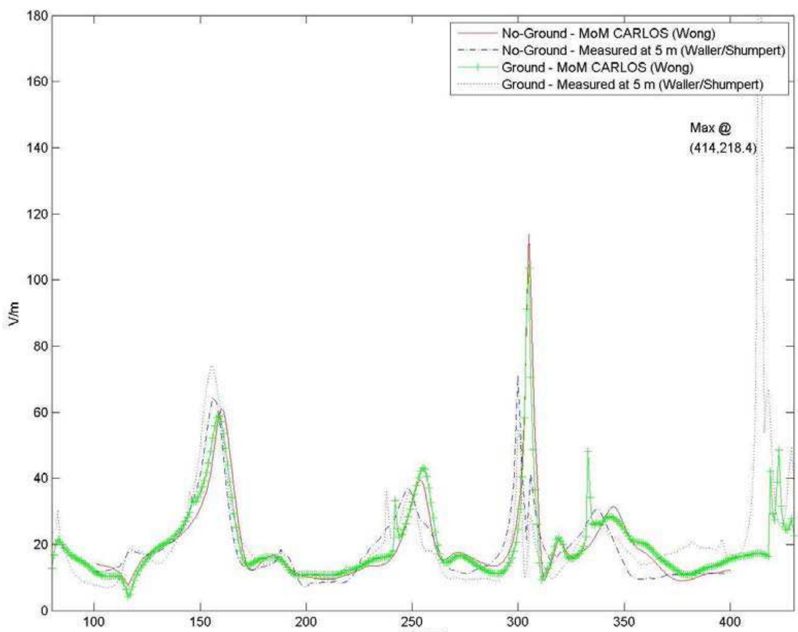

Figure 11. Internal fields, vertical/TE, measured vs. modeled.

These TM results are most encouraging. The 2-D TE formulation incorporating the infinite ground has proven to be more challenging to correlate closely with the 3-D model and the measured aperture fields. Generally speaking, the 2-D TE model exhibits much the same spectral nature as the 3-D model and concomitant measured aperture fields. However, these "coupling amplitudes" for the aperture fields for the 2-D TE model seems to be somewhat different that what is observed in the 3-D model and the measured data. Comparing the aperture field amplitudes between the 2-D model and the 3-D model, we have observed that the 2-D response exceeds the 3-D model response by as much as 10–12 dB for a cylinder height of 0.940 (37 in). Similarly, comparisons of the 2-D aperture responses for the three separate cylinder heights (0.94 m, 1.295 m, and 2.515 m) yield much wider variations in the amplitudes than what is observed in the measured data for the TE aperture fields. A fundamental question arises as to why one would expect enhanced responses for the 2-D TE case as compared to the observations in the 2-D case.

Figures 11 and 12 present similar data for the "spatially-averaged" fields (actually the normalized power densities) for the two polarizations of the incident excitation. These data again are pertinent

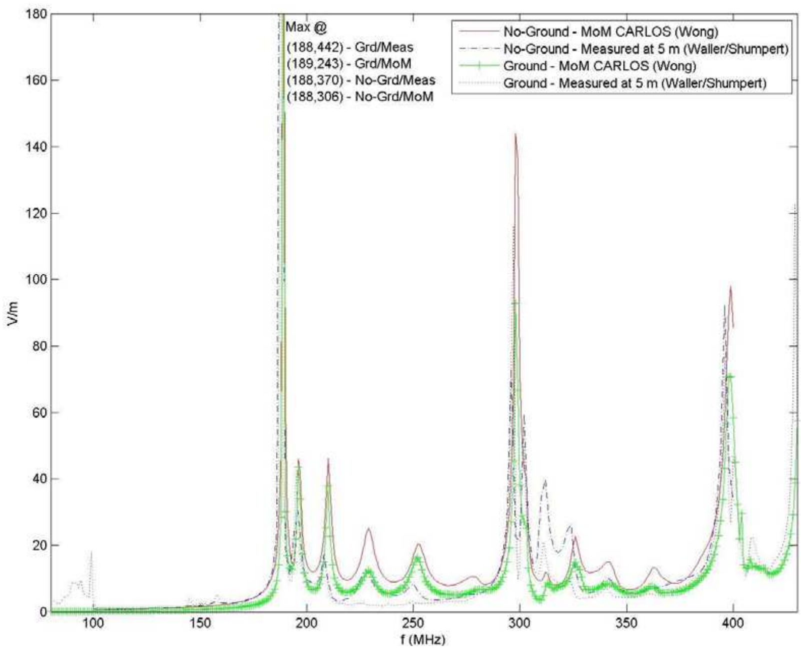

Figure 12. Internal fields, horizontal/TM, measured vs. modeled.

to considering the enhancement of the interior fields from the applied exterior fields with applications to careful considerations of controlling the Maximum Permissible Exposure (MPE) levels w/r/t personnel safety at positions interior to vehicles such as helicopters and ground vehicles during high intensity EMV testing.

3. CONCLUSIONS

The comparisons between the measured and modeled electric field amplitudes in the aperture and the "spatially-averaged" interior fields for each of the two polarization cases are remarkably similar. Also, these comparisons again suggest that the presence (or absence) of the ground plane does not result in drastic changes in the fields coupled in the aperture and into the interior of the conducting cylinder. It is evident that the presence of the ground changes some of the coupling mechanisms, but the effects are not such that measurements in the presence of the ground are not representative of what one would see if the ground were not present.

The agreement between the measured and modeled aperture fields is encouraging for both the modeler and the experimentalist. It is a rare event to see such close comparisons between the amplitudes and frequencies predicted by the three-dimensional model and the measured fields.

Calculated and measured electric fields in the slotted aperture and "spatially-averaged" fields at several interior points inside the hollow cylinder are presented and compared when radiated by a LPDA located at 5 m from the cylinder slot or from a plane wave with a "free" electric field of 20 V/m. These results confirm previous studies that electric fields interior to regions inside of conducting vehicles with apertures may exceed the applied fields by as much as an order of magnitude at specific frequencies associated with cavity resonances of the vehicles' interior regions. Such quantitative information comes directly to bear when planning and carrying out EMV testing of vehicles. "Elevated" interior fields compared to the externally applied fields require care to protect personnel who are driving, piloting, or otherwise manning equipment inside of these vehicles.

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REFERENCES

1. *Electromagnetic Environmental Effects Requirements for Systems*, Department of Defense Interface Standard, MIL-STD-464C, Oct. 1, 2010.
2. *Electromagnetic Environmental Effects (E3) Performance and Verification Requirements*, Aeronautical Design Standard, ADS-37A-PRF, May 28, 1996.
3. Scharstein, R. W., M. L. Waller, and T. H. Shumpert, "Bounds on the accuracy of the measurement of plane-wave coupling into cavity structures using near-field sources," *IEEE 2006 International Symposium on Electromagnetic Compatibility, EMC*, 102–104, Aug. 14–18, 2006.
4. Scharstein, R. W., M. L. Waller, and T. H. Shumpert, "Near-field and plane-wave electromagnetic coupling into a slotted circular cylinder: Hard or TE polarization," *IEEE Trans. on Electromagnetic Compatibility, EMC*, 714–724, Nov. 2006.
5. Waller, M. L., T. H. Shumpert, and R. W. Scharstein, "Aperture coupling near-field cavity effects for electromagnetic testing with measurements on a slotted circular cylinder," *IEEE 2010 International Symposium on Electromagnetic Compatibility, EMC*, 62–66, Jul. 25–30, 2010.
6. Waller, M. L., T. H. Shumpert, R. W. Scharstein, and S. H. Wong, "Comparison of measured vs. modeled TE and TM field penetration into a slotted circular cylinder," *Progress In Electromagnetics Research B*, Vol. 28, 201–218, 2011.
7. Beren, J. A., "Diffraction of an H-polarized electromagnetic wave by a circular cylinder with an infinite axial slot," *IEEE Trans. on Antennas and Propagation*, 419–425, May 1983.
8. Ziolkowski, R. W. and J. B. Grant, "Scattering from cavity-backed apertures: The generalized dual series solution of the concentrically loaded E-pol slit cylinder problem," *IEEE Trans. on Antennas and Propagation*, 504–528, May 1987.
9. Department of Defense Instruction, "Protecting personnel from electromagnetic fields," No. 6055.11, Aug. 19, 2009.
10. "IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz," IEEE C95.1-2005, Apr. 19, 2006.